NASA Technical Memorandum 4045

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Summary

High-power lasers in space could provide power for a variety of future missions such as spacecraft electric power requirements and laser propulsion. This study investigates four electrically pumped laser systems, all scaled to 1-MW laser output, that could provide power to spacecraft. The four laser systems are krypton fluoride, copper vapor, laser diode array, and carbon dioxide. Each system was powered by a large solar photovoltaic array which, in turn, provided power for the appropriate laser power conditioning subsystem. Each system was blockdiagramed, and the power and efficiency were found for each subsystem block component. The copper vapor system had the lowest system efficiency (0.25 percent), whereas the laser diode array had the highest efficiency (6 percent). The CO₂ laser was found to be the most readily scalable but has the disadvantage of long laser wavelength.

Although the laser diode array appears to be the most efficient electrically pumped candidate, there are major technical uncertainties with regard to phase matching, cooling, and making electrical connections to the approximately one million laser diodes required to produce a 1-MW laser beam.

Introduction

The concept of laser power transmission has been known for more than 10 years, with proposed applications such as providing electrical power for low power Earth-orbiting spacecraft (ref. 1), powering direct Earth-to-space launch (ref. 2), and propelling light-sail spacecraft to nearby stars with multigigawatt lasers (ref. 3). Proposed primary power sources have been as varied as nuclear reactors (refs. 4 and 5), solar photovoltaic cells, chemical reactions (ref. 6), and concentrated solar light.

In the early 1980's a program plan was developed (ref. 7) to direct feasibility studies and research on spacecraft-to-spacecraft laser power transmission for electrical power and propulsion applications. Civilian applications for this technology were viewed as long-range (i.e., not before the year 2000). The requirement was for reliable, continuous (CW), high average power for a multiyear mission. In analyzing the various technologies, microwave power transmission was seen as the most mature and efficient at the time but required very large transmitting and receiving antennae for good power coupling over long distances. However, lasers were developing rapidly and offered an area reduction in the transmitting and receiving systems of the order of 10⁷ times. Laser power transmission was chosen for its high payoff potential for the far term.

Three types of lasers were considered, based on their primary power source: chemical lasers, electrical lasers, and solar-pumped lasers. Chemical lasers were severely limited for useful continuous power transmission by the need to replenish large quantities of consumed lasant. Electrical lasers were being developed by industry for materials processing and by DOD for military applications. However, the complexity of and stress on the electrical systems, the civil requirements for long duration continuous high power at near visible wavelengths, and the size of the industrial and DOD programs suggested that this area should be monitored for progress but not be the focus of NASA's space-power transmission programs. Solar-pumped lasers (i.e., lasers using solar power without conversion to electricity) were uniquely suited to NASA's mission. The primary power source, the Sun, is continuous and of long duration. These lasers, while only concepts, appeared to stress materials and components less seriously than electrical lasers, and they also promised such simplicity that long-term continuous high-power operation seemed possible. Also, no one was conducting research to determine their full potential. Thus, NASA feasibility studies (ref. 1) and research (ref. 8) have focused almost exclusively on solarpumped lasers for power transmission since the early 1980's.

This report revisits electrical lasers. It seeks to answer, on a systems level, whether new electrically driven lasers appear more advantageous for NASA applications than they did when the program plan (ref. 7) was being formulated in 1981. Four electrically driven laser systems were chosen for investigation because of their potential for scaling to high-average-power systems. The systems investigated are a krypton-fluoride (KrF) excimer laser, a copper vapor laser, a solid-state laser diode array, and a carbon dioxide (CO₂) laser.

This systems study is very limited in nature and was not intended to be a point design. The study focuses on system efficiency, provides an estimate of radiator and solar panel areas, and seeks to define the key technical barriers to the realization of a high-power laser of each type. Although the design of each system includes little detail, the intercomparison between systems can produce valuable insights into the practicality of space-based electric lasers. Future studies will compare the best electric laser to direct solar-pumped laser candidates.

Electrically Driven Lasers

Each high-power electrical laser system was scaled from published information on a lower power operational system. Optimistic assumptions were made to permit linear extrapolations to a high-power system. The common design point was a long-time average 1 MW of laser power emitted from each laser system. This power level was chosen to be consistent with levels in previous studies (ref. 9).

The primary power source for each laser system was a solar photovoltaic array with an assumed overall efficiency of 20 percent. The array had its own radiator on the back of the photovoltaic cells. While other primary power sources such as solar dynamic and nuclear systems could have been used, their designs were not as well established as that of solar photovoltaics. Thus, in this preliminary study, the more established technology of photovoltaic power generation was used.

KrF Excimer Laser

Excimer lasers have advanced dramatically since the early 1980's to the point where they are being considered for inertial confinement fusion drivers. Because of their short radiative lifetime and broad emission bandwidth, these lasers emit a short pulse after a great deal of energy is deposited in the lasant.

A pulsed, electron-beam-pumped, high-pressure KrF excimer laser has demonstrated an intrinsic efficiency (laser energy emitted per energy absorbed in lasant) of more than 10 percent (ref. 10) and an extracted laser energy density of 4×10^4 J/m³. To achieve high average power, such a laser must emit a high peak power and also have a high pulse repetition frequency. The major technical difficulty is the high repetition rate needed to achieve 1 MW average power and the associated gas flow required to remove heat from the lasant.

The system was designed as a master oscillator power amplifier (MOPA) as shown in figure 1. (The master oscillator required only a small percentage of the electrical power, lasant flow, and cooling for the total system. Thus, this study emphasized only the power amplifier.) From the amplifier a pulsed laser beam at a wavelength of 248 nm emerged with a time-averaged power of 1 MW. Electron-beam pumping took place through a sidewall foil, while lasant flowed in from the bottom and out the top of the amplifier cavity. The lasant gas pressure in the amplifier cavity was 3.3 atm prior to pumping, with individual gas components of 9 parts Ar, 1 part Kr, and 0.025 part NF₃, at an inlet temperature of 300 K.

The power for laser pumping was produced and conditioned within the electrical power system shown in figure 2. This system was composed of (1) a large solar photovoltaic array providing low voltage, high current dc power at an efficiency of 20 percent; (2) a power conditioner to provide high voltage dc power

at 80 percent efficiency; (3) Marx bank capacitors and switches for periodic discharging into the Blumlein generator to produce energetic electrons; and (4) a laser cell. The Marx bank and Blumlein generator operate as a single unit with 25 percent efficiency. The electrons enter the laser cell through a thin metal foil window on one side of the cavity, creating the laser beam at 10 percent efficiency. A 1-MW laser beam is emitted from the laser cell, and 9 MW of heat is released in the lasing gas. To provide this laser power, 250 MW of solar power must be collected, requiring a solar array of 185 200 m².

The laser system power efficiency, which is the product of the efficiencies shown, is approximately 0.4 percent. An aspect worth noting is that approximately 249 MW (240 MW from electronics and 9 MW from laser gas) of thermal power must be dissipated by the system to provide 1 MW of laser power. Three radiators, in addition to that on the solar array, are needed to radiate (1) 10 MW at 300 K from the power conditioning electronics, (2) 30 MW at 373 K from the Marx bank/Blumlein generator, and (3) 9 MW at 326 K from the lasant gas. The total radiator surface requirement would be $6.3 \times 10^4 \text{ m}^2$ for these three radiators. (This does not include the solar array radiator area.) This laser would produce 840 J/pulse, and to achieve 1 MW of emitted power, it must have a pulse repetition rate of 1.2 kHz. The pumping power (781 kW/cm^3) from the 50-nsec. pulsed electron beam produces both substantial lasant heating and acoustic wave energy. Introduction of fresh lasant into the chamber to permit cool gas lasing required a gas flow system, as shown in figure 3. Primarily to avoid thermal choking, the laser amplifier size was set at 4.27 m in length, yielding a lasing volume of 21.5 L. A lasant mass flow rate of 334 kg/s was set by a flush factor of 1.5 (the number of times the chamber would be refilled with fresh lasant before the next pulse). A turbine produces 4.3 MW of mechanical power of which 4.2 MW is used to drive the compressor and 121 kW is net work. The multistage compressor provided subsonic (<Mach 0.8) flow throughout the system. Approximately 8.9 MW of thermal power must be radiated from the lasant gas circulation system, which uses a radiator temperature of 326 K.

An efficient, small, pulsed excimer laser has been scaled to a 1 MW average power, master oscillator power amplifier (MOPA) system. This preliminary effort leaves unexplored fundamental questions concerning (1) the physics of homogeneous power deposition and laser extraction from the gas, (2) the lifetime of the material to be used as the foil window through which the electron beam enters the laser cavity, (3) the minimization of lasant gas losses, and

(4) the durability of pulsed high voltage components that must operate reliably for years at more than 10^{10} pulses per year.

Copper Vapor Lasers

There are several metal vapor lasers, the most notable example being copper, that are inherently short-pulse, high temperature lasers with low lasant consumption. For space-based applications, metal vapor lasers have the advantages of a visible wavelength and high temperature operation. High temperature operation allows smaller space radiator areas. More published research was available on copper vapor lasers than on the others, thus copper was chosen as the typical electrically pumped metal vapor laser. This system has been scaled in practice to relatively high average power for laser isotope separation research.

The copper vapor laser designed for this study was pumped by a transverse discharge at a field of 1 kV/cm and had an intrinsic efficiency (laser power out/electrical power deposited) of 3 percent (ref. 11). Such lasers have exhibited specific energies as high as 650 J/m³/pulse (ref. 11). The upper-limit pulse frequency is 150 kHz (ref. 12), imposed by the time needed to depopulate the lower laser level. The laser emits simultaneously in the green at 510 nm and the yellow at 578 nm. (Since these two wavelengths are so close, simultaneous transmission of this doublet to a specific receiver does not pose a large problem; thus we treated the power at the two wavelengths as if there were only one emission line.)

The laser required 412 MW of collected solar power for the solar photovoltaic array. The array area at 20 percent efficiency is $305\,200~\text{m}^2$.

The volume of a laser with 1 MW average power, as determined from the specific energy and pulse rate above, was 10.25 L. Using a relatively simple 10-kV power supply to support the discharge implies, from the electric field requirement noted above, that the interelectrode spacing will be 10 cm. Making the beam cross-sectional shape a square produces a laser cavity as shown in figure 4(a). The electrical power to produce the laser beam of 1 MW average power was calculated from the intrinsic efficiency to be 33 MW. (The power for the required preionization was assumed to be negligible with respect to the pumping power.) At the surface of the electrodes, the current density into the plasma was 3.2 A/cm², which is within the state of the art (ref. 11).

The standard lasant pressure for a copper vapor laser is 200 torr of neon and 0.3 torr of copper. To achieve this copper vapor pressure, the laser chamber must be at or above a temperature of 1770 K. This

necessitates a ceramic laser tube, e.g., alumina with sapphire windows and refractory metal electrodes such as tantalum. (Temperature uniformity within the active volume is critical to proper operation of the laser; however, no net lasant flow is required.)

Operating copper vapor lasers are reported to have copper loss rates as low as 0.01 g/hr for a small, low-power system (ref. 12). When scaled to large aperture systems, this becomes approximately 875 kg/yr (≈ 1 ton/yr). Since there are no gas phase reactions to remove copper, and since the ceramic surface should rapidly reach equilibrium with copper vapor, the loss mechanism was probably vapor transport toward the cool windows and the formation of liquid copper on the walls. An effective copper heat pipe has been demonstrated (ref. 12) that could recycle the copper lasant. Based on this rationale, copper loss was assumed to be negligible.

A second heat pipe was needed outside the laser cavity to achieve the active volume thermal uniformity required and the lower temperatures needed at the sapphire windows. This heat pipe operates near 1770 K also but transports heat in a direction away from the ceramic walls outward to a thermal space radiator. These fins were on the outer walls of the heat pipe. This system rejected 32 MW of thermal power and, at 1770 K, required a radiating area of approximately 58 m² (fig. 4(b)). Keeping the sapphire windows outside the 1770 K hot zone (fig. 4(c)) was assumed to reduce their thermal stress to a level at which they would operate without auxiliary cooling. The laser mirrors were also assumed to operate near ambient temperature.

The electrical system that provided the power for the laser is shown in the block diagram of figure 5. This system was composed of (1) a solar photovoltaic array providing low voltage, high current dc power; (2) a power conditioner to convert low voltage dc to 10 kV dc power; (3) capacitors in a Marx bank/Blumlein generator for storing the energy and releasing it on demand; and (4) the laser cavity.

Figure 5 also lists approximate efficiencies and the power dissipated for each of the subsystems. The power efficiency of this laser, which is the product of the efficiencies shown, is approximately 0.25 percent. To produce 1 MW of laser power, 412 MW of solar power must be incident on the solar array. Of the 411 MW dissipated by the system, 379 MW appears in the electronics and 32 MW appears in the copper vapor plasma. Since the electronics must operate relatively cool, large radiating areas ($\approx 1.1 \times 10^5 \text{ m}^2$) are required. Care must be taken during the design to ensure that the high temperature radiators on the laser cavity do not heat the large, low temperature radiators cooling the electronics.

The technical challenges of a high-average-power copper vapor laser appear primarily in the laser cavity. There are certainly laser physics questions concerning scale-up. The long-term mechanical stability of the ceramic, the chemical and electrical stability of the refractory metal electrodes, the integrity of cable seals through the heat pipes and ceramic walls, the effect of acoustic waves generated with each laser pulse, and the cooling of sensitive windows and optics provide a critical set of unanswered questions.

Semiconductor Laser Diode Array

Recent technological developments (refs. 13 and 14) have produced single semiconductor laser diodes capable of continuous 1-W output power. The lasers are made by metal-organic-chemical vapor deposition (MOCVD) and have a quantum well active layer structure and double heterojunction (DH). A stripe electrode limits the emission region of the laser to 160 by 1 microns, but the fabrication technology makes feasible the construction of thousands of these regions in closely spaced arrays that can emit coherent light at wavelengths from 770 to 840 nm.

An array made up of one million such laser diodes is shown in figure 6 and would emit 1 MW of laser power. A single diode laser element is also shown; the laser emission region emits 1 W of laser power. Since the diodes operate at 30 percent (ref. 14) electrical efficiency, 2.3 MW of heat must be removed from the array. Efficient lasing requires operation at temperatures not much higher than 300 K. For a small laser array area, the thermal power radiated into space is negligible, and the array is thus dependent upon conduction for heat removal.

With the approximation that heat is generated uniformly in the volume of the array, a parabolic temperature distribution would be established through the 3 mm thickness. If the rear surface is kept at 250 K and the front surface is kept at 300 K, 1900 cm² of copper surface is required for heat conduction. A typical laser diode face (including emission area) is 300 μ m wide \times 500 μ m thick. One million such faces cover 1500 cm². Diodes and copper conductive surface total approximately 3400 cm². As an estimate, the frontal area of the array should be about 5000 cm².

The large number of diodes required would make the coherent coupling of each diode with every other diode a very difficult technical challenge. Conceivably, a Bragg reflector on the array output surface could be used to phase match the entire 0.5 m² array in order that the array have a single phase.

The entire system is shown in figure 7. The laser array diodes operate on a highly regulated low voltage, high current power supply that is ideally

matched to the solar photovoltaic array; thus a minimum of power conditioning equipment would be required. However, each laser diode may need its own power regulator. A laser array radiator (10 400 m²) operating at 250 K was provided to keep the array near 300 K. An Earth-radiation heat shield was also included.

A power block diagram is shown in figure 8. The 16.5 MW of solar power is collected by the solar array and produces 3.3 MW of electrical power. The solar photovoltaic panel area is 12 300 m². A power conditioner matches and regulates the current to the laser diode array at 100 percent efficiency. The power drives the array at 30 percent efficiency and produces a 1-MW laser beam and 2.3 MW of heat. Because of its electrical simplicity, this system has an overall conversion efficiency of 6 percent, which is about an order of magnitude greater than for any other concept. Heat rejection is simplified for the diode laser array because both the laser diode radiator and the solar cell radiator operate near the same temperature.

There are a number of technical issues that would need to be addressed to fully realize such a system. The phase locking of one million laser diodes to produce a diffraction-limited beam is far beyond current technology, although progress in this area is advancing rapidly. Phase locking the laser array is important because such an array produces the minimum beam spread and a tight beam results in a small receiver aperture. The large-scale integration of current control for each laser diode is a major Heat conduction from the laser diode array is a design concern, since diode lasers are very temperature sensitive devices. They are also sensitive to space radiation, as are associated optics: thus the radiation belts in midaltitude orbit pose a significant problem.

Carbon Dioxide Laser

The carbon dioxide ($\rm CO_2$) laser was scaled from a highly developed electric discharge laser system emitting laser radiation of 10.6 μm . The $\rm CO_2$ lasers are increasingly being used in materials processing and fabrication for industry (ref. 15). In fact, we chose to scale a readily available industrial laser to 1 MW power. A particular modular design provided by United Technology Corporation Research Center appeared to provide the highest commercially available, CW power (22 kW) from a transverse-flow $\rm CO_2$ laser system. This design was used as our starting point for first-order scaling. A wall plug electrical system efficiency of 5.5 percent had been demonstrated with this system. This wall-plug overall electrical system

efficiency was assumed to be maintained at 5.5 percent as the laser was scaled in power.

This industrial laser was scaled to 1-MW output by enlarging the laser extraction volume (assumed equal to the pumped volume). system consists of eight parallel laser units or modularized excitation chambers each having dimensions of $0.05 \times 0.3 \times 5$ m, representing the discharge gap spacing, the electrode width, and the electrode These dimensions allow the length, respectively. same current density on the surface of the electrodes as that of the industrial unit. Each laser module produced 0.125 MW of laser power and had the same laser extraction power density as the industrial unit (laser module power (0.125 MW) divided by the excitation volume or 1.67 MW/m³). The electrode gap spacing of the 1-MW system was kept the same as for the industrial system, i.e., 0.05 m, which is optimized for a 5-kV dc discharge across the CO₂/He/N₂ laser gas mixture.

Figure 9 shows a laser power block diagram, where 113.5 MW of solar energy is converted by the solar array into 22.7 MW of dc electrical power. The power conditioner converts the low voltage, high current solar cell power into high voltage (5 kV), low current power for the laser cavity. The electric power supply required for the 1-MW CO2 laser system is 1 MW/0.055 = 18.2 MW, since the electrical efficiency is 5.5 percent. The excess heat to be removed from the laser cavity is 17.2 MW. The electric discharge deposits this heat on the electrodes (10.9 MW) and in the working gas (6.3 MW). The electrodes are water cooled by a separate loop that includes a pump with a space radiator. The lasant loop needs a blower and thermal radiator. The thermal load Q to the lasant gas is based on the industrial unit that has a 13.7-percent intrinsic efficiency, or $Q = \frac{1}{0.137} - 1 = 6.32$ MW. The laser overall system power efficiency, which is the ratio of the laser power emitted to the solar power collected, is 0.88 percent.

Figure 10 shows a schematic diagram of the recycling system, which has eight 0.125-MW laser modules, a thermal radiator, and a blower to circulate the lasant gas. Using a first-order analysis, a thermodynamic cycle was developed, with the system parameter results shown in figure 10. The subscripts 1 and 2 refer to the flow parameters for the inlet and outlet of the laser cavity.

The choice of an 8-module system resulted after a few iterations in order to have the CO_2 gas temperature at the exit from the laser at a reasonable value (409 K) and maintain the Mach numbers M_1 and M_2 substantially below 1, i.e., operate with subsonic flow. The flow of the gaseous laser medium is important for the scaled-up system, since the kinet-

ics of the CO₂ laser require near room temperature operation.

Some interesting aspects of this system were as follows: No MOPA arrangement was necessary for this system. The system consisted of eight parallel oscillators with continuous dc power (or even ac power) at a moderate voltage for maintaining a diffuse discharge in the laser chambers. Scaling is by only a factor of 45, the smallest scaling factor among the four high-power laser systems considered in this study. The reference unit is commercially available, and there are no major uncertainties for a scaled-up design. The power to drive the blower and air compressor for aerowindows (laser cavity output windows) is negligible.

Although the CO₂ laser system is the most readily scalable to 1 MW power levels, there still remain a number of technical questions. The phase matching of eight oscillators, not addressed here, adds to the system complexity. The need for special exit beam aerowindows and $10-\mu m$ optics is a technical challenge. Also auxiliary power requirements, such as blower power, need to be investigated. A major technical challenge of this system is the 10.6- μ m laser wavelength. This wavelength will require much larger transmission mirrors as compared with visible wavelength lasers. Also, 10.6 μm is difficult to convert efficiently into electricity by photovoltaic means at the laser receiver, although a converter based on laser magnetohydrodynamics (MHD) and thermal cycles could be used with an associated complexity and weight penalty.

Comparison of Electrically Pumped Laser Systems

The present analysis of electrically pumped laser systems is very preliminary, and an operational design would probably be quite different than that proposed here; nevertheless, valuable insights can be gained by comparing these laser systems. Table I gives the laser wavelength, efficiencies, solar photovoltaic array power, solar panel area, radiated power, and radiator temperatures and areas for each laser system.

The laser wavelength has an important effect on the overall laser system, especially on the transmission optics. Wavelengths in the visible range are preferred, since the transmission and reception mirror area product is proportional to λ^2 . The equation for an aberration-free optical system (ref. 16) is

$$A_T A_R = \left(\frac{\pi^2}{4}\right) \lambda^2 R^2$$

where A_T and A_R are the transmission and reception mirror areas, λ is the laser wavelength, and R is the transmission range. Assuming that transmission range is constant and A_TA_R for the KrF laser is unity, then the relative A_TA_R product would vary with wavelength as shown in the following table:

	KrF	Cu	Diode array	CO_2
$\lambda, \mu \mathrm{m}$	0.248	0.51	0.8	10.6
Relative $A_T A_R$	1	4.2	10.4	1827

Since optical mirrors are heavy, high precision components, laser wavelength can significantly impact the overall laser system.

The intrinsic efficiency is the laser output power divided by the input power actually absorbed by the lasant. This efficiency runs from a low of 3 percent for the copper vapor laser to a high of 30 percent for the diode laser system. Any inefficiency appears as lasant heating and results in a potentially complex lasant cooling subsystem.

The electric efficiency, or wall-plug efficiency, is the laser output power divided by the power emerging from the power-conditioning subsystem. This efficiency indicates the penalty that is paid in converting the power from the power-conditioning subsystem into a form that can be used by the laser cavity. Here the diode laser array can most readily (efficiently) use the power from the powerconditioning subsystem.

The overall system efficiency is the solar-to-laser efficiency and is defined as the laser power output divided by the collected AMO (air mass zero) solar power input. All the laser systems are less than 1 percent except the diode laser array system, which is 6 percent. Because of the relatively low system efficiency, large amounts of AMO solar power must be collected, as shown in the next line of table I. This solar power is converted by a solar photovoltaic array at 20 percent efficiency into dc power. The electrical power generated by the solar photovoltaic array is shown on the next line.

Knowing the amount of AMO solar power needed, one can calculate the required size of the solar photovoltaic array by using the AMO solar insolation, $1.35~\rm kW/m^2$. The solar photovoltaic array areas are shown ranging from about $304~\rm \times~10^3~m^2$ to $12~\rm \times~10^3~m^2$. Such large areas dictate that the system be placed in high Earth orbit to reduce drag effects. The higher the orbit the longer the transmission range to low Earth orbit spacecraft, and thus larger transmission optics might be required. But

certainly, large solar arrays and radiators mean heavy power systems, and launch costs are proportional to mass.

Any inefficiency appears as heat in the system and must be radiated away by a thermal radiator. The next line shows the waste heat power that must be radiated into space for each system. This power does not include the waste heat created in the solar photovoltaic array, since it was assumed that the solar array had its own radiator on the reverse side of the solar cells.

The last line shows the radiator temperatures and areas (in 1000 m^2) necessary to radiate the system waste heat. The radiator area is dependent on the fourth power of the radiator temperature (T^4) . As a point of comparison, note that each radiator area is smaller than the corresponding solar photovoltaic array area.

Table I does not address the issue of the technological complexity associated with each system. These laser systems are very divergent in their levels of maturity and technical readiness. The most nearterm system would be the CO₂ laser where, in this study, off-the-shelf components were scaled to the 1-MW laser system. The most technologically immature system would be the diode laser array. Here very small arrays have operated at the near watt level, and no effort has been made to phase match very large arrays as required in this study. These issues are outlined in tables II–V, where an attempt is made to highlight the major system advantages, disadvantages, and technical issues.

Conclusion

Electrically pumped lasers in space could provide megawatt power laser output from either solar photovoltaic arrays or other prime power sources. Each system investigated (KrF, copper vapor, laser diode array, and CO₂) was scaled to the 1-MW laser output level using presently known scaling assumptions. Although each system could achieve 1-MW laser power, there were significant differences in system efficiencies, complexity, and potential scalability. The most scalable system was the CO_2 laser, but this system has a severe wavelength disadvantage. Conversely, the laser diode array has good efficiency and reasonable wavelength but is severely limited by current knowledge with regard to scaling. The KrF system has a good wavelength, but system complexity limits the probability of scaling this system. The copper vapor laser has low efficiency, the largest radiators, and serious scaling challenges, so it could be discarded with respect to the other candidates.

This study concluded that electrically pumped lasers could operate at megawatt continuous (CW)

power levels with system efficiencies of 6 percent or less. The diode laser array held the most promise because of its high overall efficiency, reasonable wavelength, and small space radiator. However, this system was the least mature, and as research progresses the assumptions in this study may become overly optimistic. Nevertheless, a more detailed review of laser diode arrays is recommended, especially with regard to phase matching large arrays.

The largest subsystem and probably the heaviest component is the solar photovoltaic array prime power source. Other prime power sources should be investigated. Also, laser diode array research should be monitored closely to refine the assumptions made in this study, especially with respect to phase matching such large arrays.

Returning to the question raised in the introduction, it now appears that at least one electrically pumped laser system has potentially high payoff. The laser diode array, if major technical challenges can be overcome, could become a major competitor to the direct solar-pumped laser. Further research is warranted in this area.

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Table I. Solar-Photovoltaic Electrically Pumped Laser Systems

	KrF excimer	Copper vapor	Diode array	CO ₂	Remarks
Laser wavelength, μm	0.248	0.510 0.570	0.8	10.6	
Intrinsic efficiency, percent	10	3	30	13.7	
Electric efficiency, percent	2.5	1.4	30	5.5	Wall-plug efficiency
Solar-to-laser					
efficiency, percent	0.40	0.25	6.0	0.88	
Solar power collected, MW	250	412	16.5	113.5	
Electric power from					
photovoltaic array, MW	50	82	3.3	22.7	20 percent efficiency
Solar panel area, m ²	185 200	305 200	12 300	84 400	$1.35 \text{ kW/m}^2 \text{ AMO}$
Thermal radiated power, MW	49	81	2.3	22	Other than solar array
Radiator temperature and					
area, K/1000 m ²	300/21.8 373/27.3	300/107 1770/0.057	250/10.4	300/9.8 409/10.8	
	$326/\underline{14.1}$		_		
Total radiator area, m^2	63	107	10	21	

Table II. KrF Laser System Technical Issues

Advantages:

Good laser wavelength for small transmission optics Basic physics of laser well developed Scaling for single-pulse KrF laser developed

Disadvantages:

Corrosive lasant gases Lasant consumption and materials incompatibility High-power mechanical (heavy) compressor/turbine required Fairly low system efficiency (0.4%)

Technical issues:

Electron-beam foil lifetime High-average-power electron-beam source Long-term lasant gas stability Reliability of electron-beam electronics Receiver for 0.24- μ m beam

Table III. Copper Vapor Laser System Technical Issues

Advantages:

Good wavelength for transmission optics High-temperature lasant reduces lasant radiator size Low lasant consumption

Disadvantages:

Low system efficiency (0.24%)
Huge waste heat radiator for electronics
Drag from large solar array requires high Earth orbit

Technical issues:

Scalability technology is not matured Short laser pulse requires high repetition rate supply

Table IV. Laser Diode Array Technical Issues

Advantages:

High system efficiency (6%)
Small and potentially least massive system
No lasant flow required
Reasonable laser wavelength
Laser diode array has good power coupling to solar array
Low waste heat generation

Disadvantages:

Low temperature laser operation requires low temperature radiator and heat removal subsystem

Very temperature sensitive

Effects of space radiation may be severe

Technical issues:

Phase matching large laser array not demonstrated Scaling present 1-W single diodes to 1-MW diode array Array cooling with heat pipes Complex electrical network for large diode array

Table V. CO₂ Laser System Technical Issues

Advantages:

Laser scaling to 1 MW most mature from present-day off-the-shelf components

Lasant is inexpensive inert gas

Reasonable system efficiencies (0.9%)

Disadvantages:

Laser wavelength requires large transmission optics Requires gas cycling and control power Windows and optics for long wavelength increase system complexity

Technical issues:

Long-term stability of infrared optics in space radiation environment Large transmission optics fabrication Phase matching several individual lasers cavities

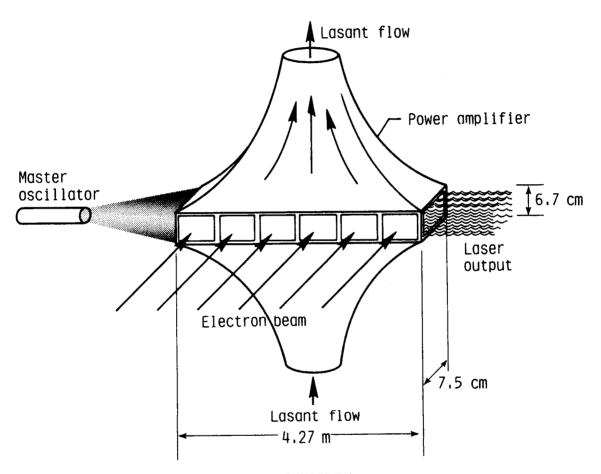


Figure 1. The 1-MW KrF laser system.

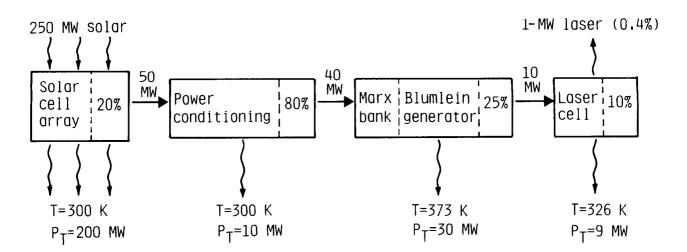


Figure 2. KrF excimer laser block diagram.

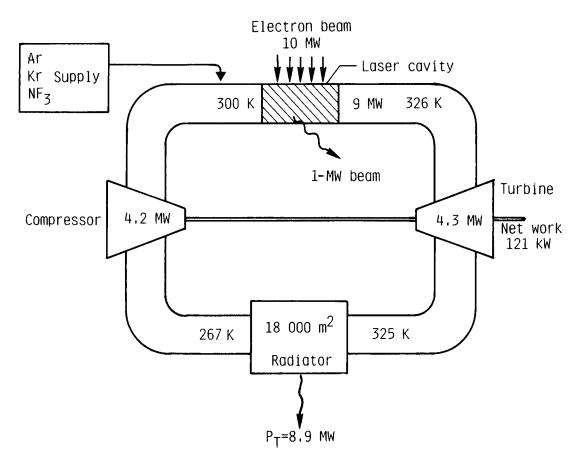
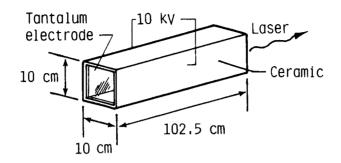
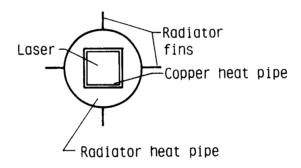


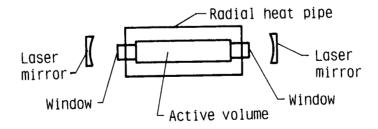
Figure 3. Lasant recirculation, cooling, and resupply system.



(a) Active volume.



(b) Thermal control heat pipe (end view).



(c) Laser cavity (side view).

Figure 4. Copper vapor laser structure.

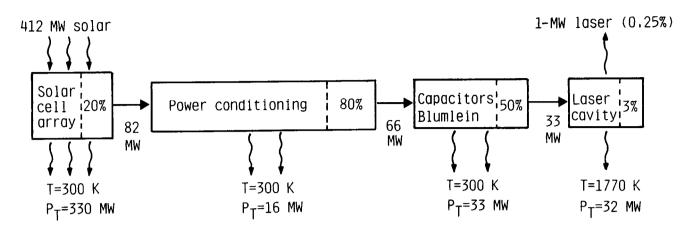


Figure 5. Copper vapor laser block diagram.

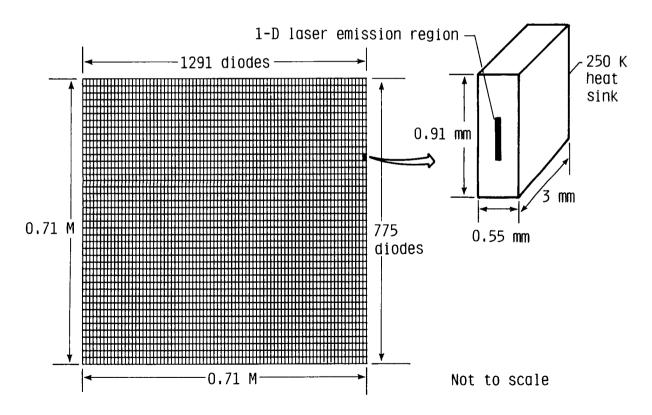


Figure 6. Two-dimensional laser diode array.

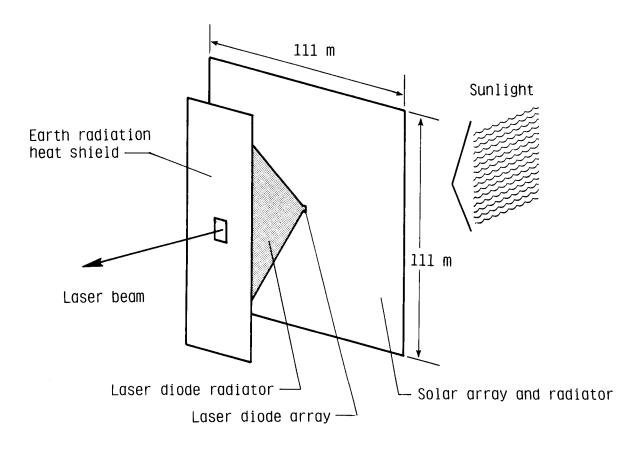


Figure 7. The 1-MW laser diode array system.

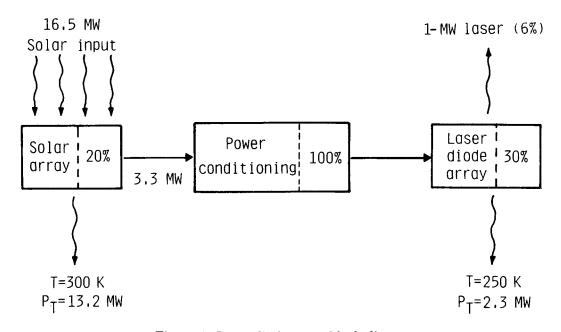


Figure 8. Laser diode array block diagram.

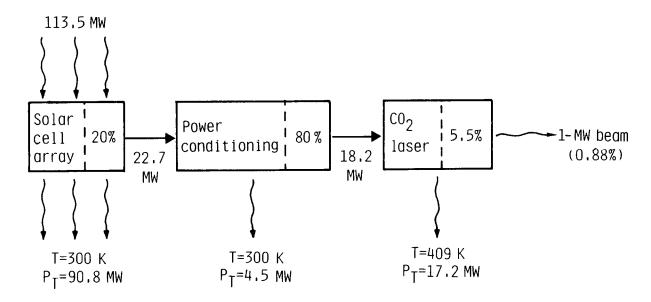


Figure 9. CO₂ laser block diagram.

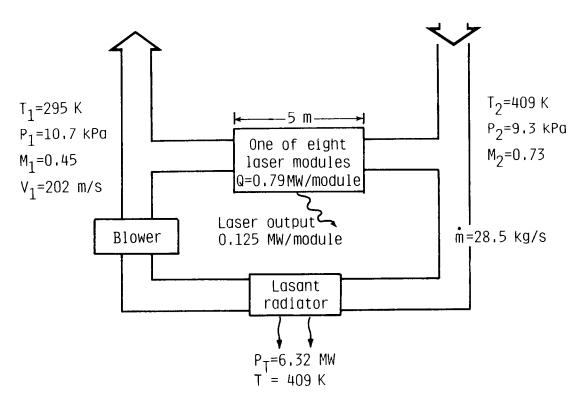


Figure 10. The CO_2 lasant recirculation and cooling system.

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electric power requiremen laser systems, all scaled t laser systems are krypton was powered by a large so laser power conditioning st were found for each subsy efficiency (0.25 percent),	ts and laser propulsion. To 1-MW laser output, tha fluoride, copper vapor, lase lar photovoltaic array which ubsystem. Each system was tem block component. Twhereas the laser diode ar	a variety of future missions such as spacecraft. This study investigates four electrically pumped at could provide power to spacecraft. The four er diode array, and carbon dioxide. Each system ich, in turn, provided power for the appropriate as block-diagramed, and the power and efficiency. The copper vapor system had the lowest system ray had the highest efficiency (6 percent). The ut has the disadvantage of long laser wavelength.
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